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叶片弯曲对跨音速涡轮叶栅流场的影响

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摘　要: 对均匀加载叶型所构成的直叶栅及不同弯角所构成的弯叶栅流场进行了数值模拟。研究了弯叶片作用下型面压力分布、马赫数等值线及叶片表面压力分布的改变, 同时考察了叶片弯曲对马蹄涡及通道涡生成位置的影响。叶片正弯后有助于减少端壁处的横向压力梯度, 削弱端壁二次流动; 另外叶片正弯后会使马蹄涡起始分离点位置向流道中间偏移, 促使通道涡提早发生。本文所选用的差分格式为具有 TVD 性质的三阶精度的 Godunov 格式, 湍流模型为修正后的 B－L 代数模型。

关　键　词: 正弯叶片; 流场参数; 数值模拟

中图分类号: O35　　文献标识码: A

1　引言

国内外很多学者对弯曲叶片降低二次流损失的机理, 进行了深入而细致的研究。文献[1] 首次指出弯曲叶片所以能够降低二次流损失, 在于叶片弯曲后在叶片表面建立了 C 型的静压分布。在该压力分布的作用下, 减少了低能流体在吸力面壁角处的堆积, 从而有效地减少了二次流损失。

文献[2] 通过试验, 详细研究了弯叶片降低二次流损失的机理。验证了文献[1] 的结论。文献[3, 4] 研究了不同冲角、不同展弦比条件下, 叶片弯曲对涡轮栅后流场的影响。本文则通过对具有代表性的正弯叶片及直叶片三维粘流场的数值模拟, 分析了叶片弯曲后对流场参数分布的改变及对涡系形成的影响, 并将这种影响与损失的变化联系起来。

2　数值方法

控制方程为任意曲线坐标系下的 N－S 方程, 差分格式为具有 TVD 性质的三阶精度的 Godunov 格式, 湍流模型为修正后的 B－L 代数模型[5] 。

本文对展弦比为 1. 3 的均匀加载涡轮静叶, 进行了弯角为正弯 15°及 30°的数值模拟。在弯、直两种情况下, 叶栅的进出口参数是相同的。进口总温为 288. 2 K, 进口总压为 1. 013×10^5 Pa, 出口背压为 0. 46×10^5 Pa, 进口为轴向进气。计算所采用的网格点数为 90×40×40。

3　叶片弯曲对流场参数的影响

图 1 给出了均匀加载叶片的直叶片与两种正弯叶片在根、中、顶三个截面上的型面压力分布。由图 1a 可以看出, 叶片正弯后根部吸力面的压力在轴向弦长 25%位置以后有较大的提升, 而压力面的型面压力在 75%位置以后也有所增加, 但其增加的幅度远不如吸力面的大。因此叶片正弯后, 根部的横向压力梯度显著下降。图 1b 所显示的顶部型面压力的变化与根部的情况基本相同, 所差异的是, 顶部压力面的型面压力在叶片弯曲之后基本保持不变, 但由于吸力面压力分布的变化, 使得顶部横向压力梯度亦有所降低。由上述讨论可知, 针对于本文所计算的叶片, 在端壁附近, 叶片弯曲使在 25%轴向弦长位置以后的横向压力梯度得以降低。对比 15°与 30°弯角这两种情况可以看出, 弯角越大, 压力梯度的降低就越明显。

由对图 1 的分析可得出如下结论: 叶片正弯后可减少端壁处的横向压力梯度, 随着弯角的增大这种变化趋势就越明显, 横向压力梯度的降低有助于削弱通道涡, 减少端壁二次流损失。

图 2 给出了均匀加载叶片在弯、直三种情况下叶栅中径处 S_1 流面 M 数等值线, 从图中可知, 叶片弯曲后, 出口 M 数有所增加, 中径附近 M 数提高带来一个直接结果是质量流量的增加。正弯 15° 质量流量增加了 2%, 而在正弯 30° 时质量流量增加了

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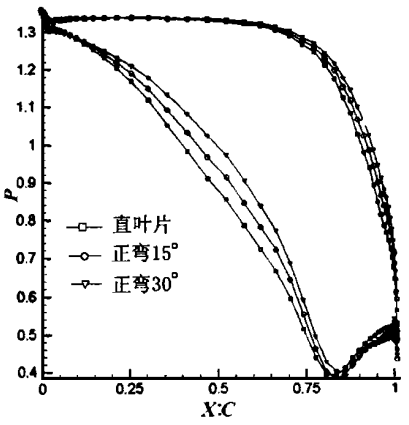
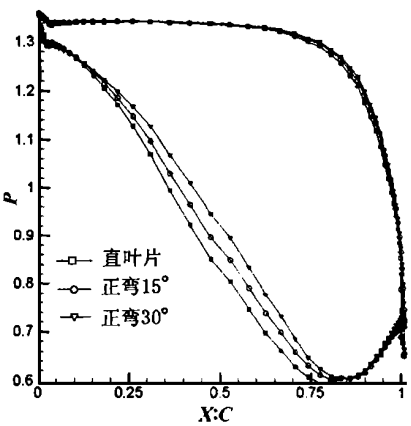


a 根部



b 顶部

图 1 叶片型面压力分布

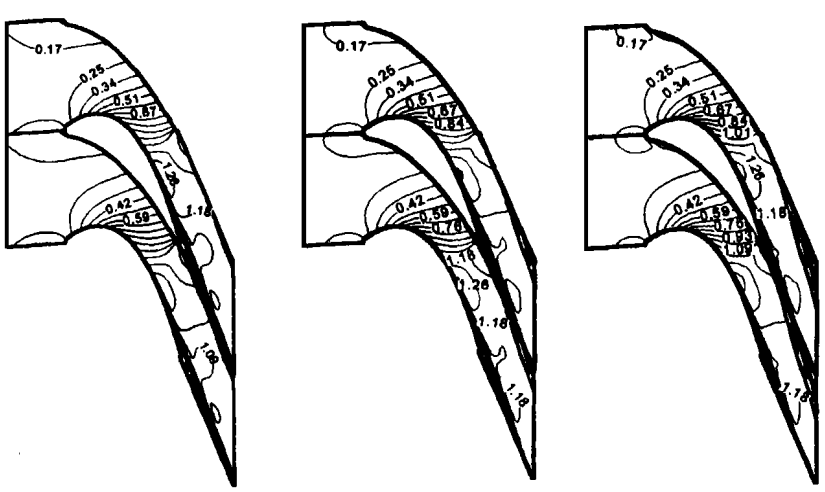
3.5%。*M* 数的提高，对损失也会有相应的影响，当出口为亚音速时，*M* 上升主要会增加叶型损失，但当出口超音速时，若在尾缘附近有激波存在，则会一方面增加激波损失，另一方面同时也使叶型损失有所增加。综合上述讨论，当设计叶片弯角时，就要求不但要考虑弯叶片对减少二次流损失的贡献，同时也要兼顾使叶片弯曲后，不致于使主流区的叶型损失及激波损失增加过大，保证弯叶片总损失的降低。

图 3 显示了均匀加载直叶片与正弯 15°及 30°叶片的压力面及吸力面的表面压力分布，从图中吸力面压力等值线的对比分析可知，正弯叶栅在吸力面附近建立起了由端壁指向中径处的压力梯度。随着弯角的增大，这种“C”型压力分布则越明显，从图中还可以看到“C”型压力分布的建立，对于 15°弯角而言，基本是在 50%轴向弦长以后，随着弯角的增大（如 30°），“C”型压力分布越明显，且其形成范围逐渐向叶片前缘扩展。根据王仲奇院士的附面层迁移理论，这种“C”型压力分布是弯叶片减少二次流损失的主要原因，即在此压力分布的作用下附面层将向叶片中部迁移，减少了叶栅出口截面附面层的堆积，可以有效地避免了出口截面附近吸力面角区处附面层的分离，从而降低了端壁附近的二次流损失。另外，研究还发现，在这种“C”型压力分布的作用下，吸力面附近壁角涡的位置将会受到很大的影响，同时也会对通道涡的位置及尺度产生一定的影响。

叶片弯曲后不但会对气动参数本身产生上述影响，同时它还将影响到叶栅内的各种集中涡及它们彼此之间的相互作用。下面就详细讨论弯叶片对马蹄涡、通道涡及壁角涡等叶栅内的几个主要集中涡的影响。

马蹄涡系不仅直接影响通道涡的强度及其沿流道的发展，从而改变叶栅的作功量和效率，而且还与前缘端壁上局部热传导和摩擦有着重要关系。叶片弯曲后将对马蹄涡系产生一定的影响。

图 4 分别给出了均匀加载叶片在正弯 15°和 30°时，根部前缘鞍点的变化。由图中鞍点的变化可得到叶片正弯后其变化规律为：鞍点位置向前，向叶栅流道内偏移，随着弯角的增大，这种变化趋势就越明显。马蹄涡的生成与发展受三个主要因素的影响，它们分别是来流附面层的厚度、流向逆压梯度及端壁法向的滞止压力梯度。这三个因素中的任何一个因素得到加强，都将促使边界层的分离、马蹄涡的生成与发展。叶片正弯后附面层将被加厚，前缘附近的流向逆压梯度及逆压梯度影响区都将变大。因此，弯叶片的马蹄涡起始分离点将向前、向流道中部偏移。



a 直叶片　　b 正弯15°叶片　　c 正弯30°叶片

图 2 中径处马赫数等值线

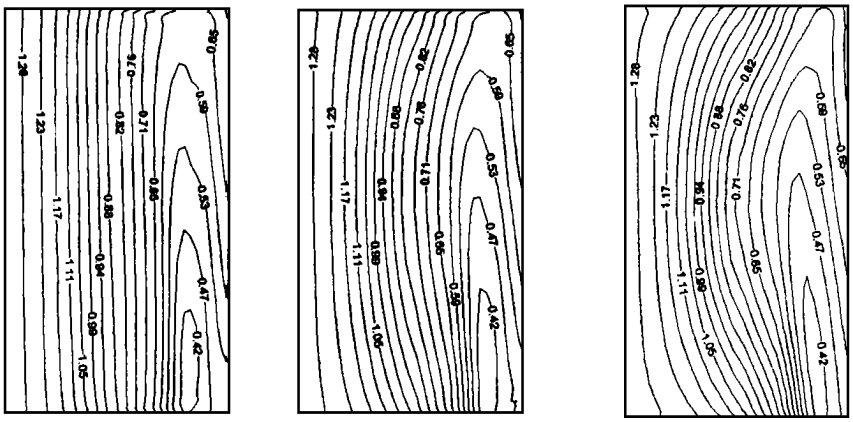
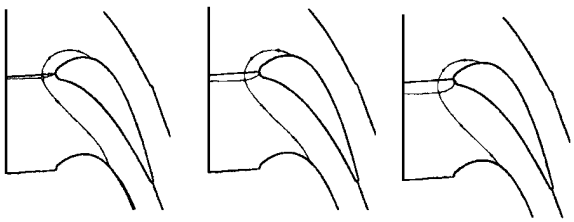
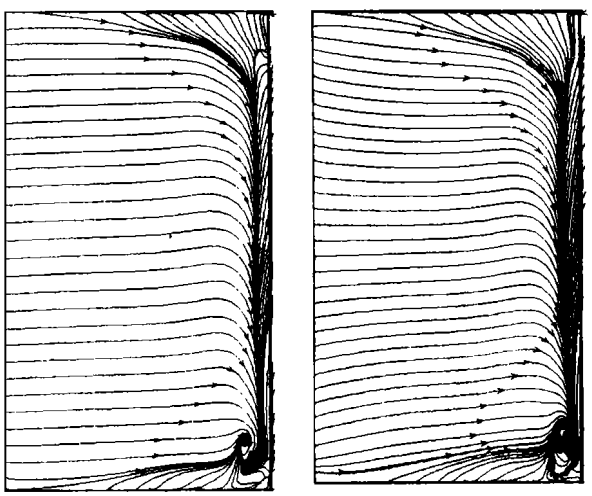


图 3　叶片吸力面压力分布



a 直叶片　　b 正弯15°叶片　　c 正弯30°叶片

图 4　根部前缘鞍点位置



a 直叶片　　c 正弯15°叶片

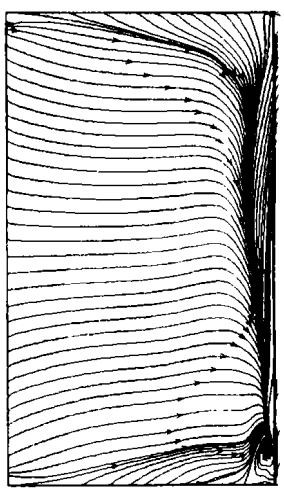
图 5　吸力面极限流线

一般说来, 通道涡生成位置处于马蹄涡压力面分支与吸力面的交点附近。从图 4 中可以看出, 叶片正弯后, 前缘鞍点及马蹄涡分离线的位置将发生改变。由于马蹄涡起始分离点及马蹄涡两个分支的分离线位置的前移, 促使马蹄涡压力面分支提早到达吸力面, 因此, 正弯叶片内通道涡将提早发生。随着弯角的增大, 通道涡的生成位置将更靠前。

叶片正弯后将建立起如图 3 所示的由端部指向叶片中部的压力梯度, 即端部压力将有所升高, 这将促使通道涡的抬升。图 5a ~ 5c 给出了均匀加载叶片在正弯 15°和 30°, 通道涡分离线与相应直叶片的差异。总的说来, 叶片正弯后, 在弯叶片吸力面"C"型压力分布的作用下, 通道涡分离线的位置将会被抬高, 向叶片中部偏移, 这将预示着弯叶片通道涡的空间位置将比相应的直叶片的高, 而且随着弯角的增大, 这种变化趋势就越明显。

4　弯叶片对损失分布的影响

图 6 给出了出口截面附近, 截距平均的能量损失系数沿叶高的分布。从图中可以看出, 叶片正弯后端部附近的损失有所下降, 其下降幅度与弯角有关, 弯角越大, 端部损失则越小。但值得注意的是, 尽管叶片正弯后可以减少端部损失, 但却使靠近流道中部的损失有所增加, 针对于本文所采用的弯曲规律, 弯角越大, 则中部附近损失增加得越明显。



b 正弯30°叶片

图 7 的损失等值线, 也显示了上述弯叶片对损失的改变规律。从图 7a 可以看出直叶片在端部的高损失区的范围最大, 正弯 15°叶片次之, 正弯 30°叶栅的端部损失最小; 对于正弯 30°叶栅而言, 损失沿整个叶高方向上的分布基本呈现出二维趋势, 即损失分布沿叶高的变化较小。可以说弯叶片有沿叶高均化损失的作用, 但这并不意味着对于任意的叶片采用任意的弯曲规律都会使损失降低, 正如本文算例所显示的那样, 弯叶片可以显著的降低端部损失但却使中部损失有所提升, 因此采用何种弯曲规律以便得到最大的收益, 要视流场的具体情况而定。

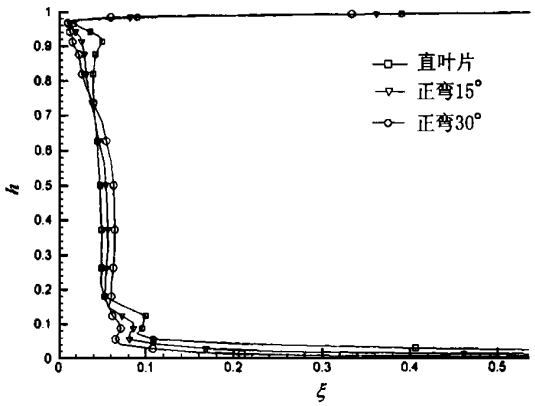
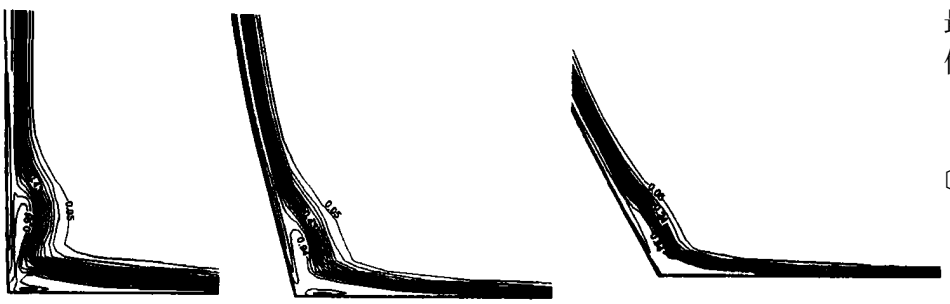


图 6 出口截面节距平均能量损失系数沿叶高的分布



a 直叶片 c 正弯15 叶片 b 正弯30 叶片

图 7 出口截面吸力面侧能量损失系数等值线

随着弯角的增大这种改变也就愈大。

(3)在吸力面将建立起"C"型压力分布,随着弯角的增大这种趋势则更加明显。因此在大弯角下,附面层向中部迁移的程度将有所提高,这会有效地减少端部二次流损失,但此时中部损失将有所增加。

(4)叶片正弯后,将降低端部压力梯度,削弱横向二次流动,随着弯角的增大这种趋势则更加明显。这表明弯叶片可以有效地降低横向压力梯度,从而控制二次流的发展。叶片正弯后,会提高中径处的出口马赫数,相应的会增加中部附近的叶型损失,对于出口有激波的流场,会使激波损失增大。

(5)弯叶片可以显著的降低端部损失但却使中部损失有所提升,因此采用何种弯曲规律以便得到最大的收益,要视流场的具体情况而定。

5 结论

本文对由常规叶片组成的直叶栅及不同弯角下弯叶栅的跨音速流场进行了数值模拟,分析了叶片弯曲后对流场气动参数及典型旋涡生成位置的影响。

(1)叶片正弯后,将使马蹄涡起始分离点的位置向前、向流道中间偏移,从而使通道涡提早发生,随着弯角的增大这种改变也就愈大。

(2)改变通道涡的空间位置。通道涡将被抬起,

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A constant change of situations in a factory demands that a steam power system should lend itself to be readily regulated within certain limits. With general composite curves serving as a tool this paper makes an analytical comparison of the steam power systems using respectively a back-pressure steam turbine unit and an extraction condensing steam turbine unit. Furthermore, a specific example is used to explain how to design a steam power system featuring a good regulation possibility with the help of the general composite curves. **Key words**: steam power system, regulation possibility, general composite curves, steam turbine

湿化器的传热传质机理和性能分析＝**Heat and Mass Transfer Mechanism and Performance Analysis of a Humidifier** [刊, 汉] / Shang Demin, Wang Yongqing, Chen Anbin, *et al* (College of Energy Science and Engineering under the Harbin Institute of Technology, Harbin, China, Post Code 150001) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —229 ~ 231, 209

Proceeding from the basic principles of heat transfer and mass transfer, the authors have set up a mathematical model for a humidifier, a major component of a humid air turbine (HAT) cycle. The humidifier performance is studied with the irrationality of some current treatment methods being identified. **Key words**: humid air turbine cycle, humidifier, heat transfer and mass transfer, work performance

有限时间内不可逆卡诺热机的最少循环时间和熵产的关系＝**The Relation Between the Minimum Cycle Time and Entropy Generation of a Finite-time Endo-irreversible Carnot Engine** [刊, 汉] / Liu Shiqiang, Yang Yushun (College of Energy Science and Engineering under the Harbin Institute of Technology, Harbin, China, Post Code 150001) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —232 ~ 234

An exploratory study is conducted of the issue of finite-time thermodynamics time. Deduced in this paper is a simple decreasing relationship between the minimum cycle time and the irreversible entropy generation of a finite-time endo-irreversible Carnot engine. It is noted that the entropy can not only mark the time arrow but also calculate the quantity of time. **Key words**: finite time thermodynamics, time, entropy generation

三种催化剂对半焦燃烧特性的影响＝**The Effect of Three Kinds of Catalyst on Semicoke Combustion Properties** [刊, 汉] / Zhu Tingyu, Wang Yang (Shanxi Provincial Institute of Coal Chemistry under the Chinese Academy of Sciences, Taiyuan, Shanxi, China, Post Code 030001) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —235 ~ 238

The combustion properties of four types of semicoke were studied with the help of a thermobalance. The results of the study show that the semicoke prepared with the addition of a catalyst possesses a relatively small MI value and a fairly good reaction activity with a small oxygen absorption quantity needed prior to a coal combustion reaction. By way of combustion dynamics calculation it is found that the semicoke prepared with calcium oxide added has the highest combustion activation. In conclusion, the conception of an average activation energy is proposed to represent an index of the semicoke combustion activity, which is compared with other combustible comprehensive index S put forward by other researchers. **Key words**: thermobalance, semicoke, combustion kinetics, average activation energy

叶片弯曲对跨音速涡轮叶栅流场的影响＝**The Effect of Turbine Blade Positive Curving on the Flow Field of a Turbine Transonic Cascade** [刊, 汉] / Wang Songtao, Wu Meng, Feng Guotai, *et al* (College of Energy Science and Engineering under the Harbin Institute of Technology, Harbin, China, Post Code 150001) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —239 ~ 242

A numerical simulation was conducted on the flow field of a straight cascade composed of uniformly loaded blades and a bowed cascade composed of blades of different curved angles. A study was performed of the change under the curved blade action of the blade profile pressure distribution, Mach number contour lines and blade surface pressure distribution.

Meanwhile, an investigation was conducted of the effect of blade curving on the location of horseshoe vortex and passage vortex formation. A positive curving of the blades has been found to be conducive to a decrease in the transverse pressure gradient at the end wall and a weakening of the end wall secondary flows. Moreover, the blade positive curving will lead to a shift of the initial separation point of the horseshoe vortex to the middle of the flow passage, bringing about a generation of the passage vortex ahead of the anticipated time. The differential scheme selected in this paper is a Godunov one of the third-order precision with TVD properties. The turbulent flow model is a B-L algebraic one after a correction. **Key words**: positive-curved blade, flow field parameter, numerical simulation

中心扩口对径向浓淡旋流煤粉燃烧器出口气固流动特性的影响＝**The Effect of a Central Flared Angle on the Gas-solid Flow Characteristics at the Outlet of a Radial Bias and Pulverized-coal Swirl Burner** [刊, 汉] / Wang Le, Wu Shaohua, Hao Jinbo, *et al* (College of Energy Science and Engineering under the Harbin Institute of Technology, Harbin, China, Post Code 150001) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —243 ~246, 263

Under the condition of different central flared angles and through the cold-state particle dynamic analyzer (PDA) testing of a radial bias and swirl burner a study was conducted of the burner outlet velocity, pulverized coal particle diameter and concentration distribution. As a result, obtained was the mechanism of the effect of the central flared angle on the gas-solid flow characteristics at the burner outlet. Also analyzed was the influence on the burner performance of the central flared angle. All the above work can provide some reference data and serve as a basis for the engineering application and optimized design of the above-mentioned burners. **Key words**: pulverized-coal swirl burner, pulverized-coal combustion, gas-solid dual-phase flow, particle dynamic analyzer (PDA)

复合型热管长度比的优化计算＝**Optimization Calculation of Length Ratios for a Composite Heat Pipe** [刊, 汉] / Adel M, Hu Yacai, Yuan Hai, *et al* (Energy Source Engineering Department, Zhejiang University, Hangzhou, Zhejiang, China, Post Code 310027) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —247 ~ 248, 255

A heat exchanger composed of gravity heat pipes with two kinds of cooling fluids has some specific features and merits in engineering applications. This paper presents a brief description of the method for determining the length ratios between the heating and cooling sections. In addition, several calculation examples are also given. **Key words**: composite heat pipe, heat pipe, length ratio

燃煤循环流化床模型与试验研究＝**Experimental Study and Simulation of a Coal-fired Circulating Fluidized Bed** [刊, 汉] / Shen Laihong (Thermal Energy Engineering Research Institute under the Southeastern University, Nanjing, Jiangsu, China, Post code 210096) // Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —249 ~251, 259

Based on the basic research results concerning the gas-solid dual-phase flow of a circulating fluidized-bed and an in-bed gas-solid bias flow model the author has set up a circulating fluidized-bed combustion model suited for different construction parameters. The model has taken into account the return mixing and the circulation process of gas and solid particles in the bed. Also considered are such a variety of factors as coal burning, the generation and dissolution of nitrogen oxides and particle wear action, etc. The results of the experimental study and model simulation on a circulating fluidized-bed combustion test rig are in good agreement with the experimental data. This fully demonstrates that the circulating fluidized-bed combustion system set up on the basis of the gas-solid dense-lean flow model can accurately simulate the combustion process of a circulating fluidized bed. **Key words**: coal, circulating fluidized bed combustion, mathematical model, experimental study

流化床风帽温度分布及其耐热性的试验研究＝**Experimental Study of the Temperature Distribution of a Nozzle Button in a Fluidized Bed and Heat Resistance of the Nozzle Button** [刊, 汉] / Wu Xin, Zhao Changsui, Duan Yufeng, *et al* (Thermal Energy Engineering Research Institute under the Southeastern University, Nanjing, Jiangsu,